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CITATION:

TSUCHIHASHI, Hiroyasu. Classification of toric singularities with simple K3 singularities as hypersurface sections. 数理解析研究所講究録 1991, 742: 111-125

ISSUE DATE:

1991-01

URL:

<http://hdl.handle.net/2433/102129>

RIGHT:

Classification of toric singularities with simple K3
singularities as hypersurface sections

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Introduction. Yonemura[8] classified the weights of non-degenerate quasi-homogeneous polynomials on \mathbb{C}^4 which define simple K3 singularities. On the other hand, to each quasi-homogeneous polynomial $f = \sum_{v \in (\mathbb{Z}_{\geq 0})^4} c_v z^v$ there exists an element u_0 in $(\mathbb{Q}_{>0})^4$ such that $\langle v, u_0 \rangle = 1$ if $c_v \neq 0$, where $z^{(m_1, m_2, m_3, m_4)} = z_1^{m_1} z_2^{m_2} z_3^{m_3} z_4^{m_4}$. Then we may regard the point u_0 as the weight of f . Let Δ^* be the convex hull of $\{v \in (\mathbb{Z}_{\geq 0})^4 \mid \langle v, u_0 \rangle = 1\}$. Then $\dim \Delta^* = 3$ and $(1, 1, 1, 1) \in \text{Int}(\Delta^*)$, if f defines a simple K3 singularity (see [8]). As a generalization of this fact, we obtain:

Theorem. Let f be a non-degenerate holomorphic function on the toric singularity $Y = \text{Spec} \mathbb{C}[\sigma^* \cap (\mathbb{Z}^4)^*]$ with $f(y) = 0$ and let $X = \{f = 0\}$, where σ^* is the dual cone of a 4-dimensional strongly convex cone σ in \mathbb{R}^4 generated by primitive elements u_1, u_2, \dots and u_s in \mathbb{Z}^4 and $\{y\} = \{x \in Y \mid z^v(x) = 0 \text{ for any } v \in (\sigma^* \cap (\mathbb{Z}^4)^*) \setminus \{0\}\}$. If (X, y) is a simple K3 singularity, then the following two conditions are satisfied.

(1) Y is Gorenstein, i.e., there exists an element $v_0 \in (\mathbb{Z}^4)^*$ such that $\langle v_0, u_i \rangle = 1$, if $\mathbb{R}_{\geq 0} u_i$ is a 1-dimensional face of σ for $i = 1$ through s .

(2) There exists an element $u_0 \in \text{Int}(\sigma)$ such that $\dim \Delta^* = 3$ and that $v_0 \in \text{Int}(\Delta^*)$, where Δ^* is the convex hull of $\{ v \in \sigma^* \cap (\mathbb{Z}^4)^* \mid \langle v, u_0 \rangle = 1 \}$.

The purpose of this paper is to show that the pairs (σ, u_0) satisfying the conditions of the above theorem are finite modulo $\text{GL}(4, \mathbb{Z})$. We can obtain all representatives of them, using a computer. However, they are too many to make a list here.

In §1, we prove the above theorem and show that there exists a partial order on the set of the pairs satisfying the conditions of the above theorem such that for a pair (σ, u_0) , all the pairs $(\tau, u_0) \geq (\sigma, u_0)$ are finite and obtained by a simple algorithm (see Proposition 1.6 and its proof).

In §2, we give a list of representatives of all the minimal pairs (σ, u_0) . We omit the proof of the completeness of the list, for the sake of its length.

§1 Toric singularities and their hypersurface sections.

Let $N = \mathbb{Z}^{n+1}$ be a free \mathbb{Z} -module of rank $n + 1 \geq 3$ and let N^* be its dual module with canonical pairing $\langle \cdot, \cdot \rangle$:

$N^* \times N \rightarrow \mathbb{Z}$. Let $\sigma = R_{\geq 0}u_1 + R_{\geq 0}u_2 + \dots + R_{\geq 0}u_s$ be an $(n+1)$ -dimensional strongly convex rational cone in $N_{\mathbb{R}}$ generated by primitive elements u_i in N . Here we may assume that $R_{\geq 0}u_i$ is a 1-dimensional face of σ for each $i = 1$ through s . Let $Y = \text{Spec} \mathbb{C}[\sigma^* \cap N^*]$ and let $z^v : Y \rightarrow \mathbb{C}$ be the character of v , which is the natural extension of $v \otimes 1_{\mathbb{C}^\times} : \text{Spec} \mathbb{C}[N^*] \simeq (\mathbb{C}^\times)^{n+1} \rightarrow \mathbb{C}^\times$, for each v in $\sigma^* \cap N^*$. Then the set $\{x \in Y \mid z^v(x) = 0 \text{ for all } v \in (\sigma^* \cap N^*) \setminus \{0\}\}$ consists of only one point y and any holomorphic function f on Y with $f(y) = 0$ is expressed as the power series:

$$f := \sum_{v \in (\sigma^* \cap N^*) \setminus \{0\}} c_v z^v.$$

Let X be a hypersurface section of Y containing y , i.e., $X = \{f = 0\}$, for a holomorphic function f on Y with $f(y) = 0$. Here we note that if (X, y) is an isolated singularity, then the dimension of the singular locus $\text{Sing}(Y)$ of Y is not greater than 1, i.e., any $(n-1)$ -dimensional face of σ is non-singular. Assume that X is normal and that $X \setminus \{y\}$ has only rational singularities. Then by [6] and [1], we obtain:

Proposition 1.1. The following three conditions are equivalent.

- (1) (X, y) is Gorenstein.
- (2) (Y, y) is Gorenstein.
- (3) (G) There exists an element $v_0 \in N^*$ such that $\langle v_0, u_i \rangle = 1$ for $1 \leq i \leq s$.

We denote the above v_0 , by $v(\sigma)$.

Definition 1.2. The Newton polyhedron $\Gamma_+(f)$ of f is the convex hull of $\cup c_v \neq 0 (v + \sigma^*)$, and the Newton boundary $\Gamma(f)$ of f is the union of the compact faces of $\Gamma_+(f)$.

Definition 1.3. We call f non-degenerate, if

$$\partial f_{\Delta^*} / \partial z_1 = \dots = \partial f_{\Delta^*} / \partial z_{n+1} = 0$$

has no solutions in $T := \text{Spec} \mathbb{C}[N^*] \subset Y$ for each face Δ^* of $\Gamma(f)$, where $f_{\Delta^*} = \sum_{v \in \Delta^* \cap N^*} c_v z^v$ and $(z_1, z_2, \dots, z_{n+1})$ is a global coordinate of T , i.e., $z_i = z^{v_i}$ for a basis $\{v_1, v_2, \dots, v_{n+1}\}$ of N^* .

Proposition 1.4. ([5, Theorem 2.2]) Assume that the condition (G) in Proposition 1.1 is satisfied and that f is non-degenerate. Then (X, y) is purely elliptic if and only if $v(\sigma) \in \Gamma(f)$. (See [7], for the definition of a purely elliptic singularity.)

Remark. If $v(\sigma) \in \partial \Gamma_+(f) \setminus \Gamma(f)$, then $X \setminus \{y\}$ has worse singularities than rational singularities.

Proposition 1.5. Under the assumption of Proposition 1.4, (X, y) is of $(0, n-1)$ -type if and only if $\dim \Delta^* = n$, where Δ^* is a face of $\Gamma(f)$ with $v(\sigma) \in \text{Int}(\Delta^*)$. (See [2], for

the definition of $(0,i)$ -type of a purely elliptic singularity.)

Proof. Let Σ be a subdivision of the dual Newton boundary $\Gamma^*(f)$ of $\Gamma(f)$ consisting of non-singular cones (see [4] and [5], for the definition of $\Gamma^*(f)$). Then $\tilde{Y} := T_N \text{emb}(\Sigma)$ and \tilde{X} are non-singular, where \tilde{X} is the proper transformation of X under the holomorphic map $p : \tilde{Y} \rightarrow Y$ obtained by the morphism of r.p.p. decompositions $(N, \Sigma) \rightarrow (N, \{\text{faces of } \sigma\})$. Let Σ_1 be the set of the 1-dimensional cones in Σ whose generators are contained in $\text{Int}(\sigma)$ and let E_τ be the intersection of the closure of $\text{orb}(\tau)$ and \tilde{X} , for each τ in Σ_1 . Then $\bigcup_{\tau \in \Sigma_1} E_\tau$ is the exceptional set of the resolution $p|_{\tilde{X}} : \tilde{X} \rightarrow X$ and we can express $K_{\tilde{X}} = (p|_{\tilde{X}})^* K_X + \sum_{\tau \in \Sigma_1} a_\tau E_\tau$. Here we note that $a_\tau = \langle v(\sigma), u_\tau \rangle - d(u_\tau) - 1$, by [5, Lemma 2.1], where u_τ is the primitive element in N generating τ and $d(u_\tau) = \min \{ \langle v, u_\tau \rangle \mid v \in \Gamma_+(f) \}$. Hence $a_\tau \geq -1$, for each τ in Σ_1 . Assume that $\dim \Delta^* = n$. Then there exists only one 1-dimensional cone τ in Σ_1 with $a_\tau = -1$ and E_τ is irreducible. Hence (X, y) is of $(0, n-1)$ -type. Next, assume that $\dim \Delta^* \leq n-1$. Then we easily see that there exist at least two 1-dimensional cones τ in Σ_1 such that $a_\tau = -1$ and that $E_\tau \neq \emptyset$. Hence (X, y) is not of $(0, n-1)$ -type. q.e.d.

Assume that f is a non-degenerate holomorphic function on Y with $f(y) = 0$ and let $X = \{f = 0\}$. When $n = 3$, (X, y) is a simple K3 singularity (, i.e., (X, y) is Gorenstein purely elliptic of $(0, 2)$ -type [3]), if and only if (Y, y) is Gorenstein, $v(\sigma)$ is contained in the interior of a 3-dimensional face of $\Gamma(f)$, by Propositions 1.1, 1.4 and 1.5. Assume that (X, y) is Gorenstein purely elliptic of $(0, n-1)$ -type. Then there exists a unique element u_0 in $\text{Int}(\sigma)$ such that $\langle v, u_0 \rangle = 1$ for any element v in the face Δ^* of $\Gamma(f)$ whose interior contains $v(\sigma)$. Hence Δ^* is contained in

$$\Delta_{\sigma}^*(u_0) := \text{convex hull of } \{ v \in \sigma^* \cap N^* \mid \langle v, u_0 \rangle = 1 \}.$$

Therefore, the pair (σ, u_0) satisfies the following condition:

$$(E) \dim \Delta_{\sigma}^*(u_0) = n \text{ and } v(\sigma) \in \text{Int}(\Delta_{\sigma}^*(u_0)).$$

Thus we obtain the theorem in Introduction. Conversely, assume that (σ, u_0) satisfies the conditions (G) and (E), and let $X = \{f = 0\}$, where $f = \sum_{v \in \Delta_{\sigma}^*(u_0) \cap N^*} c_v z^v + \text{higher terms}$, for certain non-zero complex numbers c_v . Then (X, y) is Gorenstein purely elliptic of $(0, n-1)$ -type, if (X, y) is an isolated singularity.

Problem 1. Is the set of the pairs (σ, u_0) satisfying the conditions (G) and (E), finite modulo $GL(N)$?

Let

$\tilde{\xi}^n = \{ (\sigma, u_0) \mid \sigma \text{ is an } (n+1)\text{-dimensional strongly convex rational cone satisfying (G), } u_0 \in \text{Int}(\sigma) \text{ and } u_0 \text{ satisfies (E)} \}$

and let $\xi^n = \tilde{\xi}^n / \sim$, where $(\sigma, u_0) \sim (\sigma', u'_0)$ if and only if there exists an element g in $GL(N)$ such that $g(\sigma) = \sigma'$ and that $g(u_0) = u'_0$. We define a partial order on $\tilde{\xi}^n$ as follows: $(\sigma, u_0) \geq (\sigma', u'_0)$ if and only if $\sigma \supset \sigma'$, $v(\sigma) = v(\sigma')$ and $u_0 = u'_0$. Let

$\tilde{\xi}_0^n = \{ (\sigma, u_0) \in \tilde{\xi}^n \mid (\sigma, u_0) \text{ is minimal} \}$

and let $\xi_0^n = \tilde{\xi}_0^n / \sim$, where we call (σ, u_0) minimal, if $(\sigma, u_0) \geq (\tau, u_0)$ implies $(\sigma, u_0) = (\tau, u_0)$, for any $(\tau, u_0) \in \tilde{\xi}^n$.

Remark. (1) Assume that $(\sigma, u_0) \in \tilde{\xi}^n$. If the cone τ generated by a subset of $L := \{ u \in \sigma \cap N \mid \langle v(\sigma), u \rangle = 1 \}$ is $(n+1)$ -dimensional strongly convex and contains u_0 in the interior, then $(\tau, u_0) \in \tilde{\xi}^n$, because $\tau^* \supset \sigma^*$.

(2) Since $\#L < +\infty$, for any pair (σ, u_0) in $\tilde{\xi}^n$, we have $\# \{ (\tau, u_0) \in \tilde{\xi}^n \mid (\sigma, u_0) \geq (\tau, u_0) \} < +\infty$. Hence for any pair (σ, u_0) in $\tilde{\xi}^n$, there exists a pair (τ, u_0) in $\tilde{\xi}_0^n$ with $(\sigma, u_0) \geq (\tau, u_0)$.

Let $C(\sigma, u_0) = \{ (\tau, u_0) \in \tilde{\xi}^n \mid (\tau, u_0) \geq (\sigma, u_0) \}$, for a pair (σ, u_0) in $\tilde{\xi}^n$. Then by the above remark, we have $\tilde{\xi}^n = \bigcup_{(\sigma, u_0) \in \tilde{\xi}_0^n} C(\sigma, u_0)$. Hence if ξ_0^n is a finite set, then so is

\mathcal{E}^n , by the following proposition.

Proposition 1.6. $C(\sigma, u_0)$ is a finite set, for any pair (σ, u_0) in \mathcal{E}^n .

Proof. Since for any pair (τ, u_0) in $C(\sigma, u_0)$, $\Delta_\tau^*(u_0)$ is the convex hull of a subset of the finite set $L^* := \{v \in \sigma^* \cap N^* \mid \langle v, u_0 \rangle = 1\}$, we have $\#\{\Delta_\tau^*(u_0) \mid (\tau, u_0) \in C(\sigma, u_0)\} < +\infty$. Conversely, let Δ^* be the convex hull of a subset of L^* such that $v(\sigma) \in \text{Int}(\Delta^*)$ and that $\dim \Delta^* = n$. Then $\#\{u \in (\mathbb{R}_{\geq 0}\Delta^*)^* \cap N \mid \langle v(\sigma), u \rangle = 1\} < +\infty$. Hence $C' := \{(\tau, u_0) \in C(\sigma, u_0) \mid \Delta_\tau^*(u_0) = \Delta^*\}$ is a finite set, because $\tau \subset (\mathbb{R}_{\geq 0}\Delta^*)^*$ for any pair (τ, u_0) in C' . Therefore, $C(\sigma, u_0)$ is a finite set. q.e.d.

Next, we show that for a cone σ satisfying the condition (G), all the elements u_0 in $\text{Int}(\sigma)$ satisfying the condition (E) are finite. Let $W_\sigma(v_0) = \{u \in \text{Int}(\sigma) \mid \dim \Delta_\sigma^*(u) = n, v_0 \in \text{Int}(\Delta_\sigma^*(u))\}$, for an $(n+1)$ -dimensional strongly convex rational cone σ and for an element v_0 in $N_{\mathbb{R}}^*$.

Theorem 1.7. $W_\sigma(v_0)$ is a finite set, for any $v_0 \in \text{Int}(\sigma^*)$.

Proof. For $v_1, v_2, \dots, v_j \in \sigma^* \cap N^*$, let

$W(v_1, v_2, \dots, v_j) = \{ u \in W_\sigma(v_0) \mid \langle v_1, u \rangle = \dots = \langle v_j, u \rangle = 1 \}$. For $u \in N_R$, let $W^*(u) = \{ v \in \sigma^* \cap N^* \mid \langle v, u \rangle < 1 \}$. Here we note that if $u \in \text{Int}(\sigma)$, then $W^*(u)$ is a finite set. First, take an element $u_0 \in \text{Int}(\sigma)$ with $\langle v_0, u_0 \rangle = 1$. Then for any element u in $W_\sigma(v_0)$ with $u \neq u_0$, we see that $\{ v \in W^*(u_0) \mid \langle v, u \rangle = 1 \} \neq \emptyset$. Hence $W_\sigma(v_0) \subset \{u_0\} \cup \bigcup_{v_1 \in W^*(u_0)} W(v_1)$. Here we note that if $W(v_1) \neq \emptyset$, then v_0 and v_1 are linearly independent. Next, if $W(v_1) \neq \emptyset$, then we can take an element $u_1 \in \text{Int}(\sigma)$ with $\langle v_0, u_1 \rangle = \langle v_1, u_1 \rangle = 1$, for each $v_1 \in W^*(u_0)$. Then we have $W(v_1) \subset \{u_1\} \cup \bigcup_{v_2 \in W^*(u_1)} W(v_1, v_2)$. Proceeding similarly, we finally obtain $W(v_1, \dots, v_{n-1}) \subset \{u_{n-1}\} \cup \bigcup_{v_n \in W^*(u_{n-1})} W(v_1, \dots, v_n)$. Then $\#W(v_1, \dots, v_n) \leq 1$, because v_0, v_1, \dots and v_n are linearly independent, if $W(v_1, \dots, v_n) \neq \emptyset$. Hence $\#W(v_1, \dots, v_{n-1}) < +\infty$ and $\#W_\sigma(v_0) < +\infty$. q.e.d.

Now, Problem 1 is reduced to:

Problem 2. Is the set of the cones σ satisfying the condition (G) such that $\{ u_0 \in W_\sigma(v(\sigma)) \mid (\sigma, u_0) \in \tilde{\mathcal{E}}_0^n \} \neq \emptyset$, finite modulo $GL(N)$?

Proposition 1.8. If $W_\sigma(v_0) \neq \emptyset$ for an element $v_0 \in \text{Int}(\sigma^*)$, then $\#IL_\sigma(v_0) \leq 1$, where $IL_\sigma(v_0) = \{ u \in \text{Int}(\sigma) \cap N \mid \langle v_0, u \rangle = 1 \}$. Conversely, if $IL_\sigma(v_0) = \{u_0\}$, then $W_\sigma(v_0) \subset$

$\{u_0\}$.

Proof. If $IL_\sigma(v_0) \neq \emptyset$, then for each element u_0 in $IL_\sigma(v_0)$, we have $\langle v, u_0 \rangle > 0$ for any v in $\sigma^* \setminus \{0\}$ and hence $\langle v, u_0 \rangle \geq 1$ for any v in $(\sigma^* \setminus \{0\}) \cap N^*$. Therefore, $W_\sigma(v_0) \subset \{u_0\}$, as we see in the proof of Theorem 1.7. Hence if $\#IL_\sigma(v_0) \geq 2$, then $W_\sigma(v_0) = \emptyset$. q.e.d.

§2 A list of representatives of all elements in ε_0^3 .

1. $\sigma = R_{\geq 0}(1, 0, 0, 0) + R_{\geq 0}(0, 1, 0, 0) + R_{\geq 0}(0, 0, 1, 0) + R_{\geq 0}(0, 0, 0, 1)$. See [8, Table 2.2], for u_0 .

2. $\sigma = R_{\geq 0}(0, 0, 0, 1) + R_{\geq 0}(1, 0, 0, 1) + R_{\geq 0}(0, 1, 0, 1) + R_{\geq 0}(1, 1, 2, 1)$ and $u_0 = \frac{1}{2}(1, 1, 1, 2), \frac{1}{3}(1, 1, 1, 3), \frac{1}{12}(5, 3, 4, 12), \frac{1}{8}(3, 2, 2, 8), \frac{1}{20}(7, 5, 4, 20), \frac{1}{16}(5, 4, 2, 16), \frac{1}{9}(3, 2, 1, 9), \frac{1}{5}(2, 1, 1, 5), \frac{1}{13}(4, 3, 1, 13), \frac{1}{11}(5, 2, 3, 11), \frac{1}{14}(5, 3, 2, 14), \frac{1}{16}(7, 3, 4, 16), \frac{1}{19}(4, 7, 3, 19)$ or $\frac{1}{24}(5, 9, 4, 24)$.

3. $\sigma = R_{\geq 0}(0, 0, 0, 1) + R_{\geq 0}(1, 0, 0, 1) + R_{\geq 0}(0, 1, 0, 1) + R_{\geq 0}(1, 1, 3, 1)$ and $u_0 = \frac{1}{4}(2, 1, 2, 4), \frac{1}{7}(3, 2, 1, 7), \frac{1}{5}(3, 1, 2, 5), \frac{1}{9}(5, 2, 3, 9), \frac{1}{6}(2, 3, 3, 6), \frac{1}{9}(3, 4, 3, 9)$ or $\frac{1}{2}(1, 1, 2, 2)$.

4. $\sigma = R_{\geq 0}(0, 0, 0, 1) + R_{\geq 0}(1, 0, 0, 1) + R_{\geq 0}(0, 1, 0, 1) + R_{\geq 0}(1, 1, 4, 1)$ and $u_0 = \frac{1}{2}(1, 1, 2, 2)$.

5. $\sigma = R_{\geq 0}(0, 0, 0, 1) + R_{\geq 0}(1, 0, 0, 1) + R_{\geq 0}(0, 1, 0, 1) + R_{\geq 0}(1, 2, 5, 1)$ and $u_0 = \frac{1}{4}(2, 3, 5, 4), \frac{1}{5}(2, 3, 5, 5), \frac{1}{2}(1, 1, 1, 2)$ or $\frac{1}{3}(1, 1, 1, 3)$.

$$6. \quad \sigma = R_{\geq 0}(0,0,0,1) + R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(1,2,7,1) \text{ and } u_0 = \frac{1}{2}(1,1,2,2).$$

$$7. \quad \sigma = R_{\geq 0}(0,0,0,1) + R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(1,3,7,1) \text{ and } u_0 = \frac{1}{2}(1,2,3,2).$$

$$8. \quad \sigma = R_{\geq 0}(0,0,0,1) + R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(1,3,8,1) \text{ and } u_0 = \frac{1}{2}(1,2,4,2).$$

$$9. \quad \sigma = R_{\geq 0}(0,0,0,1) + R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(1,3,10,1) \text{ and } u_0 = \frac{1}{2}(1,2,5,2).$$

$$10. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(-1,-1,0,1) + R_{\geq 0}(1,0,1,1) \text{ and } u_0 = \frac{1}{2}(0,0,1,2), \frac{1}{3}(-1,-1,1,3), \frac{1}{4}(-1,-1,2,4) \text{ or } \frac{1}{6}(-1,-1,2,6).$$

$$11. \quad \sigma = R_{\geq 0}(2,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(-1,-1,0,1) + R_{\geq 0}(1,0,1,1) \text{ and } u_0 = \frac{1}{2}(1,0,1,2).$$

$$12. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(-1,-1,0,1) + R_{\geq 0}(1,2,3,1) \text{ and } u_0 = \frac{1}{3}(2,2,3,3).$$

$$13. \quad \sigma = R_{\geq 0}(0,0,0,1) + R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(1,0,1,1) + R_{\geq 0}(-1,0,-1,1) \text{ and } u_0 = \frac{1}{3}(1,1,0,3), \frac{1}{4}(1,1,0,4) \text{ or } \frac{1}{6}(1,2,0,6).$$

$$14. \quad \sigma = R_{\geq 0}(0,0,0,1) + R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(1,0,1,1) + R_{\geq 0}(0,0,-1,1) \text{ and } u_0 = \frac{1}{3}(1,1,0,3) \text{ or } \frac{1}{4}(1,2,0,4).$$

$$15. \quad \sigma = R_{\geq 0}(0,0,0,1) + R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(1,1,2,1) + R_{\geq 0}(0,0,-1,1) \text{ and } u_0 = \frac{1}{4}(1,1,0,4).$$

$$16. \quad \sigma = R_{\geq 0}(0,0,0,1) + R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(1,1,2,1) + R_{\geq 0}(-1,-1,-2,1) \text{ and } u_0 = \frac{1}{4}(1,1,0,4).$$

$$17. \quad \sigma = R_{\geq 0}(0,0,0,1) + R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(1,1,3,1) + R_{\geq 0}(1,-1,-3,1) \quad \text{and} \quad u_0 = \frac{1}{3}(1,1,0,3).$$

$$18. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(-1,0,0,1) + R_{\geq 0}(0,0,1,1) + R_{\geq 0}(0,2,-1,1) \quad \text{and} \quad u_0 = \frac{1}{2}(0,1,0,2).$$

$$19. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(-1,0,0,1) + R_{\geq 0}(1,1,2,1) + R_{\geq 0}(-1,1,-2,1) \quad \text{and} \quad u_0 = \frac{1}{2}(0,1,0,2).$$

$$20. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(-1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(0,-1,0,1) + R_{\geq 0}(0,0,1,1) \quad \text{and} \quad u_0 = \frac{1}{2}(0,0,1,2).$$

$$21. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(-1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(0,-1,0,1) + R_{\geq 0}(1,1,2,1) \quad \text{and} \quad u_0 = \frac{1}{2}(1,1,2,2).$$

$$22. \quad \sigma = R_{\geq 0}(1,1,0,1) + R_{\geq 0}(0,0,1,1) + R_{\geq 0}(0,0,-1,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(1,0,0,1) \quad \text{and} \quad u_0 = \frac{1}{2}(1,1,0,2).$$

$$23. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(-1,0,0,1) + R_{\geq 0}(0,2,0,1) + R_{\geq 0}(0,0,1,1) \quad \text{and} \quad u_0 = \frac{1}{2}(0,1,1,2), \frac{1}{3}(0,3,1,3) \quad \text{or} \quad \frac{1}{4}(0,4,1,4).$$

$$24. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(-1,0,0,1) + R_{\geq 0}(0,3,0,1) + R_{\geq 0}(0,0,1,1) \quad \text{and} \quad u_0 = \frac{1}{2}(0,2,1,2).$$

$$25. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(-1,0,0,1) + R_{\geq 0}(0,2,0,1) + R_{\geq 0}(1,1,2,1) \quad \text{and} \quad u_0 = \frac{1}{2}(1,1,2,2).$$

$$26. \quad \sigma = R_{\geq 0}(0,0,0,1) + R_{\geq 0}(1,1,0,1) + R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(0,0,1,1) + R_{\geq 0}(1,1,-1,1) \quad \text{and} \quad u_0 = \frac{1}{2}(1,1,0,2).$$

$$27. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(0,0,1,1) + R_{\geq 0}(-1,-1,-1,1) \quad \text{and} \quad u_0 = (0,0,0,1).$$

$$28. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(1,1,2,1) + R_{\geq 0}(-1,-1,-1,1) \quad \text{and} \quad u_0 = (0,0,0,1).$$

$$29. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(1,1,3,1) + R_{\geq 0}(-1,-1,-2,1) \text{ and } u_0 = (0,0,0,1).$$

$$30. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(1,2,5,1) + R_{\geq 0}(-1,-1,-1,1) \text{ and } u_0 = (0,0,0,1).$$

$$31. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(1,2,5,1) + R_{\geq 0}(-1,-1,-2,1) \text{ and } u_0 = (0,0,0,1).$$

$$32. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(1,2,5,1) + R_{\geq 0}(-2,-3,-5,1) \text{ and } u_0 = (0,0,0,1).$$

$$33. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(1,2,7,1) + R_{\geq 0}(-1,-1,-2,1) \text{ and } u_0 = (0,0,0,1).$$

$$34. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(1,3,7,1) + R_{\geq 0}(-1,-2,-3,1) \text{ and } u_0 = (0,0,0,1).$$

$$35. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(-1,-1,0,1) + R_{\geq 0}(0,0,2,1) \text{ and } u_0 = (0,0,1,1).$$

$$36. \quad \sigma = R_{\geq 0}(2,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(-1,-1,0,1) + R_{\geq 0}(-1,0,2,1) \text{ and } u_0 = (0,0,1,1).$$

$$37. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(-1,-1,0,1) + R_{\geq 0}(-1,0,3,1) \text{ and } u_0 = (0,0,1,1).$$

$$38. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(-1,-1,0,1) + R_{\geq 0}(0,0,1,1) + R_{\geq 0}(0,0,-1,1) \text{ and } u_0 = (0,0,0,1).$$

$$39. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(-1,-1,0,1) + R_{\geq 0}(0,0,1,1) + R_{\geq 0}(1,1,-1,1) \text{ and } u_0 = (0,0,0,1).$$

$$40. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(-1,-1,0,1) + R_{\geq 0}(0,0,1,1) + R_{\geq 0}(2,0,-1,1) \text{ and } u_0 = (0,0,0,1).$$

$$41. \quad \sigma = R_{\geq 0}(1,0,0,1) + R_{\geq 0}(0,1,0,1) + R_{\geq 0}(-1,-1,0,1) +$$

$$R_{\geq 0}(1, 2, 3, 1) + R_{\geq 0}(-1, -2, -3, 1) \quad \text{and} \quad u_0 = (0, 0, 0, 1).$$

$$42. \quad \sigma = R_{\geq 0}(1, 0, 0, 1) + R_{\geq 0}(-1, 0, 0, 1) + R_{\geq 0}(0, 0, 1, 1) + R_{\geq 0}(0, 4, -1, 1) \quad \text{and} \quad u_0 = (0, 1, 0, 1).$$

$$43. \quad \sigma = R_{\geq 0}(1, 0, 0, 1) + R_{\geq 0}(-1, 0, 0, 1) + R_{\geq 0}(1, 1, 2, 1) + R_{\geq 0}(-1, 3, -2, 1) \quad \text{and} \quad u_0 = (0, 1, 0, 1).$$

$$44. \quad \sigma = R_{\geq 0}(1, 0, 0, 1) + R_{\geq 0}(-1, 0, 0, 1) + R_{\geq 0}(0, 1, 0, 1) + R_{\geq 0}(0, -1, 0, 1) + R_{\geq 0}(0, 0, 2, 1) \quad \text{and} \quad u_0 = (0, 0, 1, 1).$$

$$45. \quad \sigma = R_{\geq 0}(-1, 0, 0, 1) + R_{\geq 0}(0, 0, 1, 1) + R_{\geq 0}(2, 0, -1, 1) + R_{\geq 0}(0, 1, 0, 1) + R_{\geq 0}(0, -1, 0, 1) \quad \text{and} \quad u_0 = (0, 0, 0, 1).$$

$$46. \quad \sigma = R_{\geq 0}(-1, 0, 0, 1) + R_{\geq 0}(1, 1, 2, 1) + R_{\geq 0}(1, -1, -2, 1) + R_{\geq 0}(0, 1, 0, 1) + R_{\geq 0}(0, -1, 0, 1) \quad \text{and} \quad u_0 = (0, 0, 0, 1).$$

$$47. \quad \sigma = R_{\geq 0}(-1, 0, 0, 1) + R_{\geq 0}(0, 0, 1, 1) + R_{\geq 0}(2, 0, -1, 1) + R_{\geq 0}(0, 1, 0, 1) + R_{\geq 0}(1, -1, 0, 1) \quad \text{and} \quad u_0 = (0, 0, 0, 1).$$

$$48. \quad \sigma = R_{\geq 0}(0, -1, 2, 1) + R_{\geq 0}(0, 2, 0, 1) + R_{\geq 0}(1, 0, 0, 1) + R_{\geq 0}(-1, 0, 0, 1) \quad \text{and} \quad u_0 = (0, 0, 1, 1).$$

$$49. \quad \sigma = R_{\geq 0}(0, 0, 2, 1) + R_{\geq 0}(0, 3, 0, 1) + R_{\geq 0}(1, 0, 0, 1) + R_{\geq 0}(-1, 0, 0, 1) \quad \text{and} \quad u_0 = (0, 1, 1, 1).$$

$$50. \quad \sigma = R_{\geq 0}(1, 0, 0, 1) + R_{\geq 0}(-1, 0, 0, 1) + R_{\geq 0}(0, 1, 0, 1) + R_{\geq 0}(0, -1, 0, 1) + R_{\geq 0}(0, 0, 1, 1) + R_{\geq 0}(0, 0, -1, 1) \quad \text{and} \quad u_0 = (0, 0, 0, 1).$$

$$51. \quad \sigma = R_{\geq 0}(1, 0, 0, 1) + R_{\geq 0}(-1, 0, 0, 1) + R_{\geq 0}(0, 1, 0, 1) + R_{\geq 0}(0, -1, 0, 1) + R_{\geq 0}(1, 1, 2, 1) + R_{\geq 0}(-1, -1, -2, 1) \quad \text{and} \quad u_0 = (0, 0, 0, 1).$$

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